



## Full length article

# Buckling of cold-stretched cylindrical vessels under external pressure: Experimental and numerical investigation



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## ABSTRACT

Cold-stretching is an important lightweight technology for reducing cost of cryogenic vessels, which are widely used for storing liquefied gas. This paper studied the influence of cold-stretching on the buckling behavior of cylindrical vessels with different initial out-of-roundness under external pressure. Buckling pressures, strains, and buckling modes of cylindrical vessels were obtained from experiments. A 3D laser scanner was used to obtain the complicated geometry of the vessels before and after cold-stretching. Based on the 3D scanned geometry, we performed FEA to evaluate the buckling pressures, which resulted in a good agreement with the experimental values. The effects of cold-stretching on buckling are discussed based on four factors: out-of-roundness, thickness, diameter and yield strength. Firstly, buckling of cylindrical vessels is elastic buckling in our case, so yield strength has no influence on buckling pressure. Secondly, the negative effect of diameter-thickness ratio increasing was proved to be slight (within 3.3%) in our case. Finally, buckling pressure increased after cold-stretching because out-of-roundness decreased. Experiments showed that buckling pressures were enhanced by 10.8% and 13.6% after cold-stretching for long and short cylindrical vessels with 1.9% and 1.6% in out-of-roundness.

## 1. Introduction

Cold-stretched cryogenic vessels are widely used in the world for storage of liquid nitrogen, liquid oxygen, and liquid natural gas, due to their distinguished performances such as lighter weight in comparison with conventional products [1]. When an austenitic stainless steel is loaded in tension to a strengthening stress above its yield strength and then unloaded, the steel is cold-stretched. Cold-stretching method could increase the allowable stress of the steel. Compared with convention methods, cold-stretched products are material-saving, and have lower weight-volume-ratio. External pressure is an important load for cold-stretched vacuum insulated cryogenic vessels. For example, when the container need to perform the helium tight test, the inner vessel may endure 0.1 MPa external pressure; in the process of filling insulating material into the insulating interlayer space, the inner vessel may be subjected to an external pressure of about 0.05–0.1 MPa. In such cases, buckling is an important failure mode. Therefore, it's necessary to perform external pressure design for cold-stretched vacuum insulated cryogenic vessels according to design codes [2,3], for which cylindrical vessel is an important part.

Two kinds of changes after cold-stretching process may affect the

elastic buckling of thin cylindrical vessels under external pressure. On the one hand, diameter-thickness ratio may increase and this would result in the decreasing of external pressure stability [4]. On the other hand, the shape of the cylindrical vessel may be improved and its out-of-roundness may decrease after cold-stretching, and these changes would result in the increasing of external pressure stability. In literatures, numerous studies have been taken regarding the buckling of imperfect pressure vessel components loaded by external pressure [5–7]. Schneider and Brede [8] studied the effects of geometric imperfections on buckling behavior of steel cylindrical shells, and they concluded that single longitudinal imperfections were suited to achieve the experimentally determined buckling resistances. Frano and Forasassi [9] investigated the effects of geometric imperfection like eccentricity, ovality and welded joint geometry on the buckling behavior, and they concluded that ovality reduced the buckling pressure significantly. Fatemi et al. [10] studied the buckling behavior of imperfect cylindrical shells and they concluded that as the depth of the initial imperfection got larger, buckling pressure of thin walled shells under external pressure decreased significantly. Karampour and Alberman [11] presented experimental and FEA results for buckle interaction in subsea pipelines, and concluded that the structural response of a

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**Nomenclature**

$d_1$	measured diameter before cold-stretching, mm
$d_2$	measured diameter after cold-stretching, mm
$D_i$	design inside diameter of cylindrical vessel, mm
$D_{max}$	measured maximum outside diameter of cylindrical vessel, mm
$D_{min}$	measured minimum outside diameter of cylindrical vessel, mm
$D_o$	design outside diameter of cylindrical vessel, mm
$e_1$	out-of-roundness before cold-stretching
$e_2$	out-of-roundness after cold-stretching
$E$	Young's modulus, MPa
$K_D$	outside diameter scaling factor, the ratio of the outside diameter of the cylindrical vessel after transformation to its original diameter
$K_L$	length scaling factor, the ratio of the cylindrical vessel length after transformation to its initial value
$K_\theta$	shape deviation scaling factor, the ratio of the out-of-roundness after transformation to its initial value
$L$	design length of cylindrical part of cylindrical vessel, mm
$L_c$	critical length, mm
$p_{cr}$	buckling pressure calculated by U.S. Experimental Model Basin formula, MPa

$p_E$	experimental buckling pressure, MPa
$p_F$	FEA buckling pressure, MPa
$p_C$	buckling pressure of cylindrical vessel with cold-stretching, MPa
$p_N$	buckling pressure of cylindrical vessel without cold-stretching, MPa
$p_0$	FEA buckling pressure of cylindrical vessel with 303.67 mm in diameter and 1.84 mm in thickness, MPa
$p_x$	FEA buckling pressure of cylindrical vessels with different diameter and thickness, MPa
$R_0$	outside radius of cylindrical vessel, mm
$t_c$	design thickness of cylindrical part of cylindrical vessel, mm
$t_h$	design thickness of ellipsoidal head, mm
$t_1$	average thickness before cold-stretching, mm
$t_2$	average thickness after cold-stretching, mm
$x, y, z$	initial coordinates of data points of cylindrical vessel surface, mm
$x', y', z'$	coordinates of data points of cylindrical vessel surface after transformation, mm
$\nu$	Poisson's ratio
$\sigma_{UTS}$	ultimate tensile strength, MPa
$\sigma_{yp}$	yield strength, MPa

pipeline was strongly influenced by its initial imperfections. What's more, yield strength may increase after cold-stretching as mentioned in Refs. [12,13]. As discussed in Ref. [14], plastic buckling pressure is in proportion to yield strength. So higher yield strength would improve plastic buckling pressure. Owing to this contradiction, it's necessary to determine whether the buckling of thin cylindrical shells is elastic or plastic buckling. And it's imperative to study whether the buckling pressure increase or decrease after cold-stretching, and the variation extent of buckling pressure after cold-stretching.

EN 13458 Annex C (informative) *Pressure strengthening of vessels from austenitic stainless steels* [3] states "If the pressure strengthened vessel is made from solution heat treated material the safety factors  $S_k$  (3 for cylinders) given in 4.3.2.4 can be replaced by  $S_k/1.5$ ". Thus, EN 13445 recognizes the positive influence of cold-stretching that the shape of the pressure vessel produced by cold-stretching could be improved. To prove this modification, previously in our lab Chen [4] established a nonlinear analysis method to simulate the cold-stretching process and investigate its influence on the buckling pressures of cylindrical vessels, and the results showed that buckling pressures of cylindrical vessels with large out-of-roundness increased after cold-stretching. But there are some shortcomings in Ref. [4]. Firstly, there was no experiment to prove the simulation method and the results. Secondly, the research assumed that the section at one-half of the axial length of the cylindrical vessel was oval. It was not based on actual shapes of cylindrical vessels. Finally, short cylindrical vessels of only one dimension with different out-of-roundness were considered. Long cylindrical vessels were not investigated. Those shortcomings are one of the motivations of this paper.

In this paper, we present the experimental investigation on the buckling behavior of the cold-stretched stainless steel cylindrical vessels subjected to external pressure. Some cylindrical vessels were buckled after cold-stretching, whereas the others were buckled without cold-stretching. Before experiments, we measured initial shapes of cylindrical vessels by a 3D laser scanner. Buckling pressures were also determined numerically according to the measured initial shapes. Based on experimental and numerical results, the role of cold-stretching on buckling of cylindrical vessels was studied.

## 2. Experimental methods

### 2.1. Test vessels

The selection of geometric dimensions was based on the fact that long and short cylindrical vessels have different buckling modes. Formula (14) in Ref. [15] was used to calculate the critical length to distinguish long and short cylindrical vessels, as shown in formula (1). When the cylindrical part of a cylindrical vessel is longer than the critical length, it's defined as long cylindrical vessel, otherwise, it's defined as short cylindrical vessel.

$$L_c = 1.11D_o \sqrt{D_o/t_c} \quad (1)$$

All vessels were manufactured with two integral ellipsoidal heads, as shown in Fig. 1. Six long cylindrical vessels were designed and manufactured from thin stainless steel, with inner diameter 87 mm, thickness 1 mm, and length 950 mm. The long cylindrical vessels were divided into three pairs, designated here as (L11, L12), (L21, L22), and (L31, L32). In the same way, six thin austenitic stainless steel short cylindrical vessels, with inner diameter 300 mm, thickness 2 mm, and length 700 mm, were designated here as (S11, S12), (S21, S22), and (S31, S32). And three backup both long and short cylindrical vessels were also fabricated. Each pair, e.g. group P1, is a set of two vessels (e.g. L11, L12) with similar out-of-roundness. The out-of-roundness of three pairs increase in sequence. Lifting jacket was used to produce the out-of-roundness. For cylindrical vessels in each pair, one (e.g. L11) was compressed to buckle without cold-stretching, and the other (e.g. L12) was compressed to buckle after cold-stretching, as shown in Table 1. The cold-stretching process was according to GB/T 18442-2011 [2] and EN 13458-2: 2002 [3]. Nominal thicknesses of ellipsoidal heads for long and short cylindrical vessels were thicker than their cylindrical shells, to make sure the test vessels buckled at the cylindrical shells instead of ellipsoidal heads. One longitudinal butt joint existed along each cylindrical shell. The design parameters of cylindrical vessels are summarized in Table 2.

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